

X-ray plateaus followed by sharp drops in GRBs 060413, 060522, 060607A and 080330: Further evidences for central engine afterglow from Gamma-ray Bursts

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Abstract The X-ray afterglows of GRBs 060413, 060522, 060607A and 080330 are characterized by plateaus that are followed by very sharp drops. An X-ray plateau is interpretable within the framework of the external forward shock model but the sharp drop is not. In this work we interpret these peculiar X-ray afterglow data as the central engine afterglows from some magnetized central engines, plausibly magnetars. In this model, the X-ray afterglows are powered by the internal magnetic energy dissipation and the sudden drop is caused by the collapse of the magnetar. Accordingly, the X-ray plateau photons should have a high linear polarization, which can be tested by the future X-ray polarimetry.

Key words: gamma-rays: bursts - ISM: jets and outflows - radiation mechanisms: nonthermal

1 INTRODUCTION

Gamma-Ray Bursts (GRBs) are by far the most luminous objects in the universe. They are bright flashes of high energy photons. A typical GRB usually lasts about several or tens of seconds. In the standard fireball model, the prompt γ -ray emission is powered by the internal shocks (Paczynski & Xu 1994; Rees & Mészáros 1994; Kobayashi et al. 1997; Daigne & Mochkovitch 1998; Spruit et al. 2001; Fan, Wei & Zhang 2004), and the GRB afterglows are the emission of the external forward shock driven by the GRB fireball expanding into the surrounding medium (Mészáros & Rees 1997; Sari et al. 1998; Dai & Lu 1998a; Chevalier & Li 2000; Huang et al. 2000). The fireball afterglow model has been widely accepted because it works pretty well on reproducing the late time multi-wavelength afterglow data in the pre-*Swift* era (e.g., Sari et al. 1998; Panaitescu & Kumar 2002; Piran 2004).

The GRB central engine may also play an important role in producing afterglow emission, i.e., the so-called “central engine afterglow” (Katz, Piran & Sari 1998; Fan, Piran & Xu 2006). One disadvantage of this model is its lack of predictive power. Though somewhat ad hoc, people began to interpret the data with this model. For example, Piro et al. (1998) discovered a late-time outburst of the X-ray afterglow of GRB 970508 and attributed such an outburst to the re-activity of the central engine. However, the energy injection model can reproduce the multi-wavelength outburst data quite well (Panaitescu et al. 1998). So the late time

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outburst detected in GRB 970508 is not a good *central engine afterglow* candidate. The situation changed dramatically in 2005. Piro et al. (2005) discovered two very early X-ray flares in GRB 011121, which had been interpreted as the central engine afterglow—the prompt emission powered by the re-activity of the central engine (Fan & Wei 2005). Since then, more and more X-ray flares have been well detected in early afterglow (e.g., Nousek et al. 2006), and their central engine origin has been well established (e.g., Zhang et al. 2006).

In view of the similarity of the temporal behaviors of X-ray flares and GRBs, it is not a surprise to see that they have a common origin. Central engine afterglows may be a bit more common than previously thought. People found out that even some power-law decaying X-ray afterglows might have a central engine origin. A good example may be the afterglow of GRB 060218. As shown in Fan et al. (2006), the inconsistency of the X-ray afterglow flux with the radio afterglow flux and the very steep XRT spectra support here the central engine afterglow hypothesis (see Zhang et al. 2007, Liang et al. 2008 for more cases). Recently, Troja et al. (2007) argued that the X-ray plateau followed by a sharp drop in GRB 070110 is also a central engine afterglow.

In this work, we discuss the optical and X-ray afterglow of GRB 060607A. We show that not only the early X-ray plateau followed by a sharp drop but also the very early optical re-brightening may be due to the prompt emission of the long activity of the central engine. This result suggests that the central engine optical/X-ray afterglows might be common. We also apply the central engine afterglow model to quite a few more bursts, including GRB 060413, GRB 060522 and GRB 080330.

2 OBSERVATIONS

GRBs 060413, 060522, 060607A, 070110 and 080330 are different in many aspects, for example, their redshifts and the isotropic energies of the prompt γ -ray emission (Molinari et al. 2007, Liang, Zhang, & Zhang 2007, Tueller et al. 2006, Ledoux et al. 2006). However, their X-ray afterglows share a common character. As schematically plotted in Fig.1, an X-ray flat segment with a luminosity $L_x \sim 10^{47} - 10^{48} \text{ erg s}^{-1}$ is evident in the early afterglow phase (see Tab.1 for details). The plateau disappeared suddenly with a decline as steep as t^{-4} or even t^{-8} . The optical afterglow of GRB 060607A is characterized by an optical flare hidden in the first optical re-brightening. The optical flare drops with time as t^{-11} (see Figure 2 of Nysewander et al. 2007). These peculiar behaviors are inconsistent with the regular afterglow model and may shed some lights on the central engine.

3 INTERPRETATION OF THE DATA

Quite a few physical processes are able to give rise to an X-ray flat segment. Below we discuss three of them, including the energy injection model, the density jump model, and the central engine afterglow model.

3.1 Energy injection model

We assume that the GRB central engine does not die after the prompt γ -ray emission. Such a long living central engine has an energy output $L \propto t^{-q}$ (Cohen & Piran 1999 and Zhang & Mészáros 2001), where $q \geq 1$ represents the weak energy injection and $q = 0$ corresponds to the early time energy injection from a fast rotating pulsar/magnetar (Dai & Lu 1998b; Zhang & Mészáros 2001; Dai 2004; Fan & Xu 2006). Other q values are possible if an energy injection results from slower material progressively catching up (viz. the Lorentz factor of a GRB has a wide range) (Rees & Mészáros 1998; Kumar & Piran 2000) or if an energy injection is caused by the fall-back of the envelope of the massive star (MacFadyen, Woosley & Heger 2001).

If the energy injection is significant enough, the dynamics of the forward shock will be modified. So is the afterglow light curves (Zhang et al. 2006). For the X-ray plateau, $\nu > \max\{\nu_c, \nu_m\}$ is usually satisfied, where ν is the observer's frequency, ν_c is the cooling frequency and ν_m is the forward shock typical synchrotron radiation frequency (Sari et al. 1998). Under this condition, the temporal decline index of the X-ray afterglow should be

$$\alpha = \frac{(2p-4) + (p+2)q}{4}, \quad (1)$$

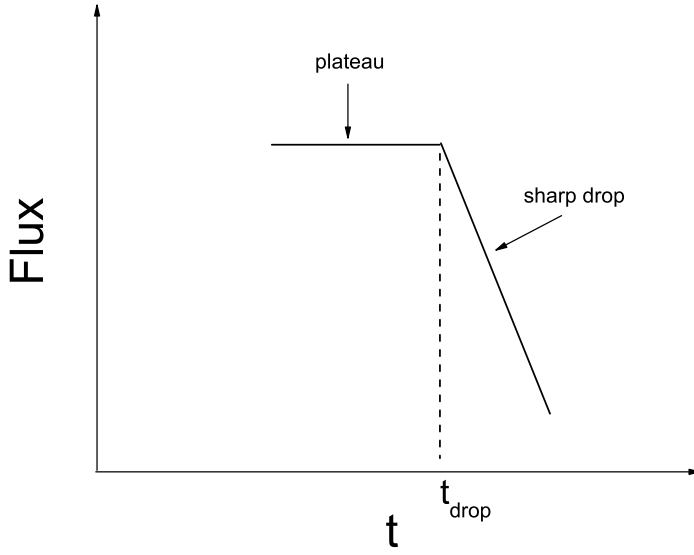


Fig. 1 —The plateau followed by a sharp drop is another central engine afterglow.

where $p \sim 2.3$ is the energy distribution power-law index of the shocked electrons in the blast wave. In GRB 060607A, the decay of the plateau before the sharp drop can be approximated $t^{-0.1}$. Taking $p \sim 2.3$, we have (note that now $\alpha \sim 0.1$)

$$q \sim 0,$$

which is consistent with a pulsar/magnetar energy injection. Similar conclusions can be drawn for X-ray flat segments detected in GRBs 060403, 060522, 070110 and 080330, too.

In this model, the X-rays are the synchrotron radiation of electrons accelerated by the forward shock. Their decline is determined by the dynamics of the forward shock and by the spherical curvature of the blast wave. Usually the decline should be shallower than t^{-p} (see Piran 2004 and Zhang 2007 for reviews). With a typical $p \sim 2.3$, the decline shallower than $t^{-2.3}$ is not steep enough to account for the sharp drops detected in GRBs 060413, 060522, 060607A, 070110 and 080330 ($\alpha = 4 \sim 8$). So the energy injection model is disfavored in these particular cases.

3.2 Density jump model

Dai & Lu (2002) proposed a density jump model to account for some afterglow re-brightening. In this model, if the density jump is large enough, strong reverse shock emission forms and will give rise to strong X-ray/UV/optical emission (cf. Nakar & Granot 2007). The decline of the afterglow light curves will be suppressed, too. So it is potentially to account for the X-ray flat segments that detected in GRBs 060413, 060522, 060607A, 070110 and 080330. However, currently the forward and reverse shock regions move with the same bulk Lorentz factor. The curvature effect of the reverse shock emission is the same as that of the forward shock emission. As shown in many literatures (e.g., Fenimore et al. 1996; Kumar & Panaitescu 2000; Fan & Wei 2005; Zhang et al. 2006; Liang et al. 2006), because of the spherical curvature of the emitting region and because of the special relativity effect, the external forward shock emission can not drop with time more quickly than

$$F_\nu \propto t^{-(2+\beta)}, \quad (2)$$

where β is the spectral index of the X-ray emission. The only exception is that the ejecta is so narrow that we have seen its edge. If true the optical emission would show the same behavior, which is not the case. We then conclude that the density jump model is not a good candidate to interpret the X-ray plateaus followed by sharp drops.

Recently Nysewander et al. (2007) employed the density jump model to account for the optical re-brightening detected in GRB 060607A. We, however, find out that the first optical flare hidden in the re-brightening (see their Figure 2) has a very steep decline $\sim t^{-11}$, which violates the curvature effect constraint seriously. Therefore, such an interpretation is problematic.

3.3 Central engine afterglow model

Some authors have discussed the energy injection of a pulsar/magnetar wind and its influence on the afterglow emission (Dai & Lu 1998b and Zhang & Mészáros 2001). Strong magnetic energy dissipation (e.g. via reconnection) may take place if the continued outflow from the central engine is Poynting-flux dominated (Fan, Zhang & Proga 2005; Gao & Fan 2006; Giannios 2006), as that happened in the phase of prompt γ -ray emission (Usov 1994; Thompson 1994; Lyutikov & Blandford 2003). In this case, part of the magnetic energy of the outflow will be converted into the delayed prompt emission, maybe mainly in X-ray band, before they inject into the forward shock.

Here following Gao & Fan (2006) and Troja et al. (2007), we discuss the central engine afterglow powered by a millisecond magnetar. It is well known that the spin-down timescale of a millisecond magnetar can be estimated as

$$T_{\text{em}} = 4 \times 10^3 \text{ s} (1+z) I_{45.3} B_{p,15}^{-2} P_{0,-3}^2 R_{s,6}^{-6}, \quad (3)$$

where $B_{p,15} = B_p/10^{15}$ Gauss is the dipole radiation magnetic field of the pulsar in units of 10^{15} Gauss, $P_{0,-3}$ is the initial rotation period in milliseconds, $I_{45.3}$ is moment of inertia in units of $2 \times 10^{45} \text{ g cm}^2$, $R_{s,6}$ is the stellar radius in units of 10^6 cm .

The dipole radiation luminosity is

$$L_{\text{dip}} \approx 10^{49} \text{ erg s}^{-1} B_{p,15}^2 R_6^6 P_{0,-3}^{-4} [1 + \frac{t}{T_{\text{em}}}]^{-2}. \quad (4)$$

We have $L_{\text{dip}} \propto t^0$ for $t \ll T_{\text{em}}$ and $L_{\text{dip}} \propto t^{-2}$ for $t \gg T_{\text{em}}$.

For such a Poynting-flux-dominated flow, the dissipation of the magnetic fields may produce X-ray/ γ -ray emission (Usov 1994; Zhang & Mészáros 2002; Fan et al. 2005). In this work we adopt the so-called MHD approximation breakdown model (Usov 1994). By comparing with the pair density ($\propto r^{-2}$, r is the radial distance from the central source) and the density required for co-rotation ($\propto r^{-1}$ beyond the light cylinder of the compact object), one can estimate the radius r_{MHD} at which the MHD condition breaks down $r_{\text{MHD}} \sim (2 \times 10^{15}) L_{\text{dip},48}^{1/2} \sigma_1^{-1} t_{v,m,-3} \Gamma_2^{-1} \text{ cm}$ (e.g. Zhang & Mészáros 2002; Fan et al. 2005), where σ is the ratio of the magnetic energy flux to the particle energy flux, $t_{v,m}$ is the minimum variability timescale of the central engine, and Γ is the bulk Lorentz factor of the outflow. Beyond this radius, intense electromagnetic waves are generated and outflowing particles are accelerated (Usov 1994). This converts magnetic energy into radiation. At r_{MHD} , the comoving magnetic fields B_{MHD} can be estimated as $B_{\text{MHD}} \sim 50 \sigma_1 t_{v,m,-3}^{-1} \text{ Gauss}$. At r_{MHD} , the typical synchrotron radiation frequency of the accelerated-electrons can be estimated as (Fan et al. 2005)

$$\nu_{\text{m,MHD}} \sim 6 \times 10^{16} \sigma_1^3 C_p^2 \Gamma_2 t_{v,m,-3} (1+z)^{-1} \text{ Hz}, \quad (5)$$

where $C_p \equiv (\frac{\epsilon_e}{0.5})^{[13(p-2)/3(p-1)]}$, ϵ_e is the fraction of the dissipated comoving magnetic field energy converted to the comoving kinetic energy of the electrons, and the accelerated electrons distribute as a single power-law $dn/d\gamma_e \propto \gamma_e^{-p}$. According to this model, a σ much larger than 10 is disfavored.

The cooling Lorentz factor of the accelerated-electrons can be generally estimated as $\gamma_{e,c} \sim 4.5 \times 10^{19} \Gamma / (r_{\text{MHD}} B^2)$, which is $\sim 10^3$ for typical parameters taken here and is comparable to $\gamma_{e,m}$. So the synchrotron radiation of the accelerated electrons peaks in the soft X-ray band. The energy emitted in X-ray band, of course, is just a fraction (ϵ_x) of the total magnetic energy dissipated, so we have

$$L_x \sim \epsilon_x L_{\text{dip}} \sim 10^{48} \text{ erg s}^{-1} \epsilon_{x,-1} B_{p,15}^2 R_6^6 P_{0,-3}^{-4} [1 + \frac{t}{T_{\text{em}}}]^{-2}. \quad (6)$$

Now we have a set of free parameters $(B_p, P_0, I, R_s, \epsilon_x)$ but just two observation data, L_x and the sharp drop time

$$t_{\text{drop}} \sim f T_{\text{em}} \sim 4 \times 10^3 \text{ s } (1+z) f I_{45.3} B_{p,15}^{-2} P_{0,-3}^2 R_{s,6}^{-6}, \quad (7)$$

where f is also a free parameter. So these free parameters can be fully determined by the limited observation data. Below we fix (B_p, P_0, I, R_s) with the typical values $\sim (10^{15} \text{ Gauss}, 1\text{ms}, 2 \times 10^{45} \text{ g cm}^2, 10^6 \text{ cm})$ and then constrain ϵ_x and f , respectively. The results are shown in Tab.1. We do not want to over-interpret the results because the typical values of (B_p, P_0, I, R_s) adopted here might be biased, so are the derived ϵ_x and f . Anyhow for GRB 060413, GRB 060607A and GRB 070110, the parameters are largely reasonable and thus support the millisecond magnetar central engine hypothesis. For GRB 060522 and GRB 080330, $E_x \approx t_{\text{drop}} L_x / (1+z) \sim 10^{50} \text{ erg}$ is significantly smaller than the total rotation energy of a millisecond magnetar $\sim I(2\pi/P_0)^2/2 \sim 4 \times 10^{52} I_{45.3} P_{0,-3}^{-2} \text{ erg}$. Possibly these two magnetars were hypermassive and collapsed before losing significant fraction of the rotation energy and angular momentum (Fan & Xu 2006). Alternatively the magnetic field of the magnetars decayed suddenly for some unknown reasons (Troja et al. 2007). The current data are not sufficient for us to distinguish between these two possibilities. In the future the gravitation wave observation may shed some lights on the nature of the X-ray drop because the collapse of the hypermassive magnetar may give rise to interesting gradational signals.

Table 1

Fit to the central engine afterglows of several GRBs, where B_p , R_s , I and P are fixed.

GRBs	$t_{\text{drop}}(\text{s})$	z	$L_x(\text{erg/s})$	ϵ_x	f	F_{ν_v}/F_{ν_x}
GRB 060413	2×10^4	3	1.02×10^{48}	0.4	1.2	3.4
GRB 060522	4×10^2	5.11	2.48×10^{48}	0.2	0.02	5.2
GRB 060607A	1.5×10^4	3.08	1.71×10^{48}	0.4	0.9	10
GRB 070110	2×10^4	2.35	2.7×10^{47}	0.1	1.4	1.4
GRB 080330	1.0×10^3	1.51	1.12×10^{47}	0.01	0.1	62

Reference.—<http://www.swift.ac.uk/>, Liang, Zhang, & Zhang 2007, Troja et al. 2007.

Notes.— For GRB 060413 we set $z \sim 3$, the typical redshift of Swift GRBs.

The prolonged activity of the central engine should also produce some emission in the optical band. A simple estimate is the following. The synchrotron self-absorption frequency can be estimated as (e.g., Fan & Wei 2005)

$$\nu_a \sim 2 \times 10^{14} \text{ Hz } [2/(1+z)]^{3/7} L_{\text{dip},48}^{2/7} \Gamma_2^{3/7} r_{\text{MHD},15}^{-4/7} B_{\text{MHD},2}^{1/7}, \quad (8)$$

which is below the optical band $\nu_v \sim 5 \times 10^{14} \text{ Hz}$. With $\gamma_{e,m} \sim \gamma_{e,c}$ and $\nu_{m,\text{MHD}} \sim \nu_x \sim 7.2 \times 10^{16} \text{ Hz}$, the optical central engine afterglow flux is not expected to be dimmer than

$$F_{\nu_v} \sim F_{\nu_x} (\nu_v/\nu_x)^{1/3} \sim 0.2 F_{\nu_x}. \quad (9)$$

Consequently the observed optical emission should be brighter than $\sim 0.2 F_{\nu_x}$, which is consistent with the observations, as shown in Tab.1.

4 DISCUSSION AND CONCLUSIONS

In contrast to what was believed in the pre-*Swift* era, it is evident now that the central engine plays an important role in producing afterglow emission (see Fan, Piran & Wei 2008 for a review). Most theoretical works so far focus on the energetic flares that are well detected in many *Swift* GRBs. The temporal behavior of the flaring X-rays are quite similar to that of the prompt γ -rays. It is thus reasonable that the flares and the prompt GRB have a common origin. In this work, we show that the X-ray plateaus followed by sharp drops detected in GRBs 060413, 060522, 060607A, 070110 and 080330 are also good candidates of the so-called “central engine afterglow” (see also Jin & Fan 2007; Troja et al. 2007; Staff et al. 2007). The energy injection model and the density jump model are less favored. We also find out that both the luminosity and the timescale of the X-ray plateaus detected in GRBs 060413, 060522 and 070110 are well consistent with the central engine afterglow emission powered by millisecond magnetars (see section 3.3

for details). For GRB 060522 and GRB 080330, the X-ray drop appeared so early that might suggest that the two magnetars, if they were, had collapsed before losing a significant part of their rotation energies and angular momentums. Though millisecond magnetar are believed to be a natural outcome of the collapse of a massive star, the identification of such a kind of compact objects at cosmological distances is not easy. Fairly speaking, additional independent signature, like a high linear polarization (see Fan, Xu & Wei 2008), is needed before the magnetar wind dissipation model for the X-ray plateaus that are followed by X-ray drops can be generally accepted.

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